Acoustic Measurements of Tiny Optically Active Bubbles in the Upper Ocean

Svein Vagle
Ocean Sciences Division
Institute of Ocean Sciences
9860 West Saanich Road
P.O. Box 6000
Sidney, BC, V8L 4B2
Canada
phone: (250) 363-6339   fax: (250) 363-6798   email: Svein.Vagle@dfo-mpo.gc.ca

LONG-TERM GOALS

In this project, which is closely linked to a separate project where the goal is to measure wave induced bubble clouds and their effect on radiance in the upper ocean (N000140710754), we intend to address the disturbing fact that despite the fundamental importance of optical backscatter in the ocean it is still not possible to explain more than 5 to 10 percent of the particulate backscattering in the ocean based on known constituents even during periods with no active wave breaking (Terrill & Lewis, 2004). One hypothesis is that very small bubbles that have been stabilized by surfactants may be responsible for part of the "missing" backscatter. The long-term goal of this project is to detect these small bubbles and to determine their concentration using acoustic techniques.

OBJECTIVES

The main objective is to modify an existing instrument design to allow for *in situ* measurements of bubbles over a wide range of bubble radii from approximately 500 micrometer at the upper end and down to less than 5 micrometer. We are pushing the technology to its limit with a goal of reaching bubble radii as small as 1 micrometer. We now have three systems where we obtain data at frequencies as high as 1MHz, corresponding to a smaller bubble radius limit of 3 micrometer. These systems were incorporated into the RadyO Scripps Pier experiment in January 2008 and the benign sea state experiment conducted in Santa Barbara channel during September 2008. In further laboratory studies during the winter of 2008-2009 we will explore whether we can push the frequency range to 2MHz, corresponding to bubbles with radii as small as 1.5 micrometer.

One interesting aspect of these particular measurements will be to investigate how these tiny bubbles, if they exist, develop from the breaking wave bubble size distributions and how the distribution and number density of these bubbles evolve following storms and periods with and without wind and wave breaking. Data are now available from the Santa Barbara channel study to investigate these issues.

APPROACH

Different acoustical techniques utilizing the resonant behaviour of small bubbles have for some time been used to obtain bubble size distributions in the ocean (e.g., Vagle and Farmer, 1998). These approaches make use of the fact that bubbles will resonate at a frequency proportional to their size and

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that the resulting scattering cross section of these bubbles is orders of magnitude higher than the corresponding geometrical scattering cross section from a particle of the same size, i.e. the bubbles have minimal damping of the incoming acoustical waves and therefore have high Q factors. (This fact also makes acoustical techniques less prone to effects from other particles in the sampling volume, a problem that often becomes critical in optical bubble sizing techniques).

The freely flooding acoustical resonator, pioneered by H. Medwin allows bubble size measurements through inversion of the bulk acoustic properties of the fluid (Farmer, Vagle & Booth, 1998; 2005). A reverberant cavity between two parallel plates is ensonified with broadband noise producing multiple resonant modes that are detected with a hydrophone. Excitation of the bubbles modifies the bulk complex sound speed of the fluid leading to attenuation and frequency changes of the resonator response. By utilizing the broadband sensitivity of the resonator both resonant and off-resonant contributions to acoustic properties over a wide frequency range provide data that are inverted to recover the distribution of bubbles of different sizes within the cavity. The instrument operates at low signal intensity, justifying application of linear acoustical theory to the inversion. Near-continuous transmission of sound into the cavity avoids uncertainties in the time dependent acoustic response of bubbles to short pulses and multiple reflections of the reverberant signal increase the effective signal-to-noise of the device.

We are building on acoustical resonator technology developed over a number of years with support from ONR to measure open ocean bubbles with radii between 15 and 500 micrometer using acoustical frequencies between 4 kHz and 200 kHz (Farmer, Vagle & Booth, 1998; Vagle & Farmer, 1998; Farmer, Vagle & Booth, 2005). The frequency spacing of the resonant peaks in the resonator depends on the size of the resonant cavity and is approximately 6 kHz in the current design. A numerical model of the operation of these devices combined with laboratory experiments show that the characteristics of their operation depend on the size of the cavity, the thickness and density of the reflecting plates, the piezoelectric film used to generate and receive the acoustical signals and the input electrical signals.

WORK COMPLETED

Our present version of the resonator is now capable of operating at acoustical frequencies up to 1MHz, corresponding to a lower bubble radius of approximately 3.2 μm. The size of the electronics has been reduced and the instrumentation now has all sound generation and receive-electronics close to the resonator transducers with digital data being transmitted back to the logging computer. This significantly improves the signal to noise ratio of the system and reduces the number of vulnerable cables required from 4 to 1.

In January 2008 the acoustical bubble resonator was tested in the surf-zone from Scripps Pier, both as a stand alone instrument and as integrated with the WET Labs' Multi-Angle Scattering Optical Tool (MASCOT) instrument a SATLANTIC fish-eye lens camera (Figure 1). The main reason for integrating these sensors was to allow for comparisons between acoustically obtained bubble size distributions and distributions obtained from the optical sensors. Figure 2 shows a comparison between the acoustical resonator and the MASCOT instrument when a bubble plume sweeps by the sensors during of of the surf-zone deployments off Scripps Pier.
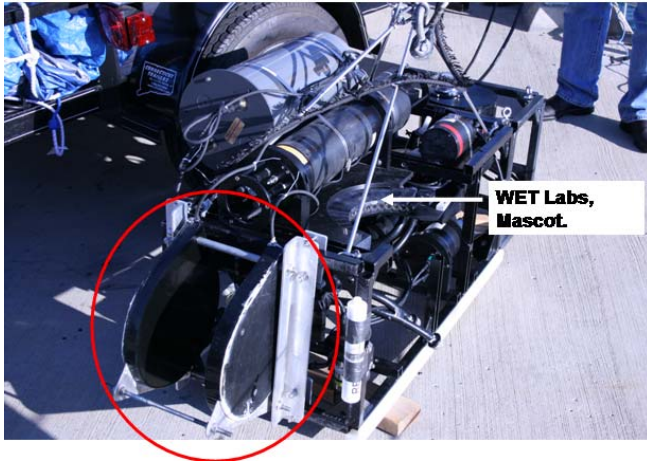
Figure 1. The RadyO acoustical resonator insonifying bubbles at frequencies between 10 kHz and 1 MHz attached to the WET Labs' MASCOT frame as deployed from Scripps Pier in January 2008 and from the R/V Kilo Moana in Santa Barbara Channel in September 2008. All resonator electronics is contained in the light grey pressure housing shown in the upper left hand corner of the photograph. The right photo show the package in the surf zone shortly after a wave breaking took place.
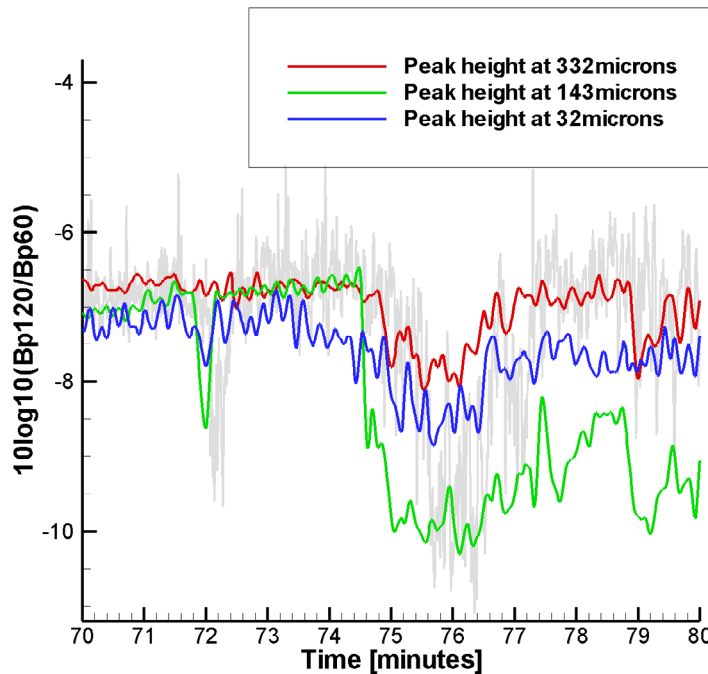

Figure 2. A ten minute comparison between acoustically and optically detected bubble plumes from the surf-zone at Scripps Pier. The grey line shows the response of β(120)/ β(60) from the MASCOT and the red, green and blue lines show the relative attenuation of sound at frequencies corresponding to resonant bubble radii of 32, 143, and 332 micrometer. Note that even though the two sensors were on the same instrument package, sample volumes were separated by about 60 to 70 cm.

Preliminary analysis of the Scripps Pier data indicate that very few bubbles with radii less than 5-6 µm were present in this very energetic zone which is dominated by very high air-fractions and large short-lived bubbles. The area around the Pier is characterized by significant alongshore and offshore running currents, quickly pulling the bubbles away from the active breaker zone.

During the recent Santa Barbara Channel experiment a resonator was again deployed with the WET Labs MASCOT frame from the stern of the R/V Kilo Moana. Especially, during periods with limited wave breaking activity it is clear that we observed acoustical resonator spectra in which it is highly likely that bubbles smaller than 5 µm were present. An example of this is shown in Figure 3, showing the observed resonator spectrum at one time (Fig. 3(a)) and the ratio of this spectrum to the spectrum 2 seconds later (Fig. 3(b)).
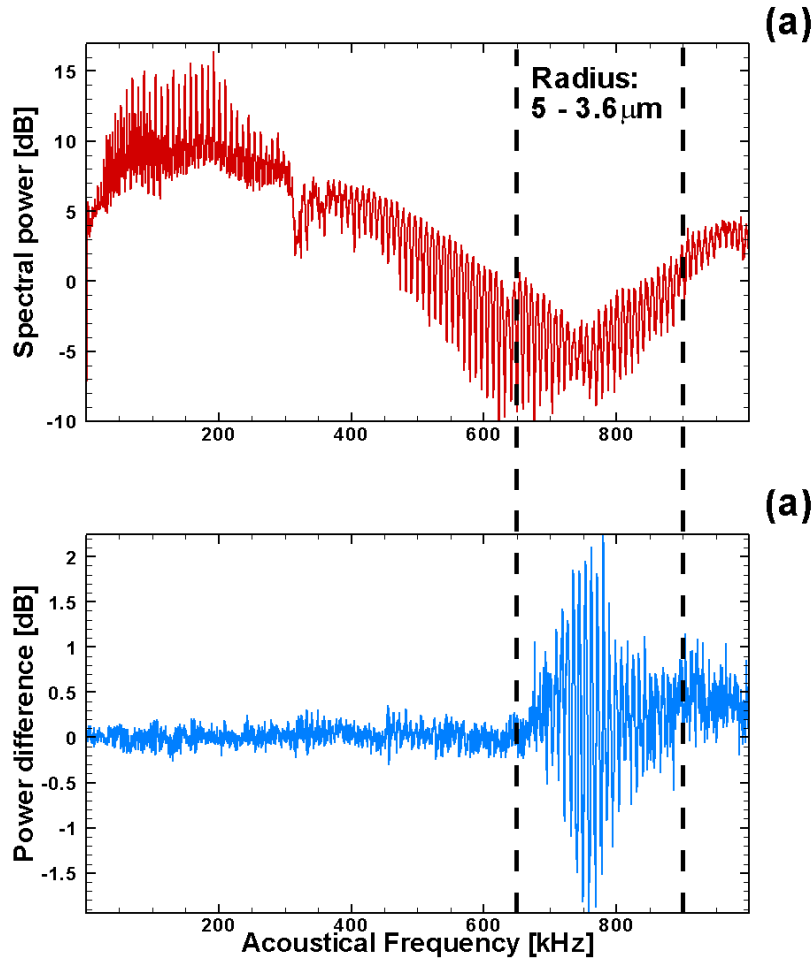

Figure 3. Acoustical response of the bubble resonator used in the Santa Barbara Channel RadyO experiment. The sensor was deployed with the WET Labs MASCOT package off the stern of the R/V Kilo Moana. The vertical spikes in (a) correspond to resonant peaks in the sensor. When bubbles are present in the resonator cavity they will extract energy from these peaks resulting in a detectable reduction in the size of the peaks. Due to the resonant characteristics of bubbles a given acoustical frequency will correspond to a certain bubble size. The lower figure (b) shows the ratio of two individual spectra separated in time by approximately 2 seconds. The significant peaks observed at frequencies between 650 and 900 kHz suggest the presence of bubbles with radii between 3.6 and 5 µm.

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It is highly suggestive from the data shown in Figure 3(b) that in this particular case bubbles with radii between 3.6 and 5 μm where present. We are presently working on inversion routines to use on these data to obtain the actual bubble size distributions from the data collected onboard R/P FLIP, R/V Kilo Moana, and in the surf zone at Scripps Pier.

RELATED PROJECTS

The development of a high-frequency, tiny bubble detection device is being utilized in the closely associated RadyO project N000140710754. In this project the goal is to measure and model bubble injection and radiance fluctuations in the upper ocean during wave-breaking conditions. However, the instrumentation developed here will also support the interpretation of most of the other RadyO projects when bubbles are present. Two of the three acoustical resonators will be also be used during the upcoming ONR sponsored SPACE08 experiment at Martha's Vineyard Coastal Observatory (MVCO) (N000140710759) in October and November 2008.

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